RUDDER/FIN SEAL INVESTIGATIONS FOR THE X-38 RE-ENTRY VEHICLE

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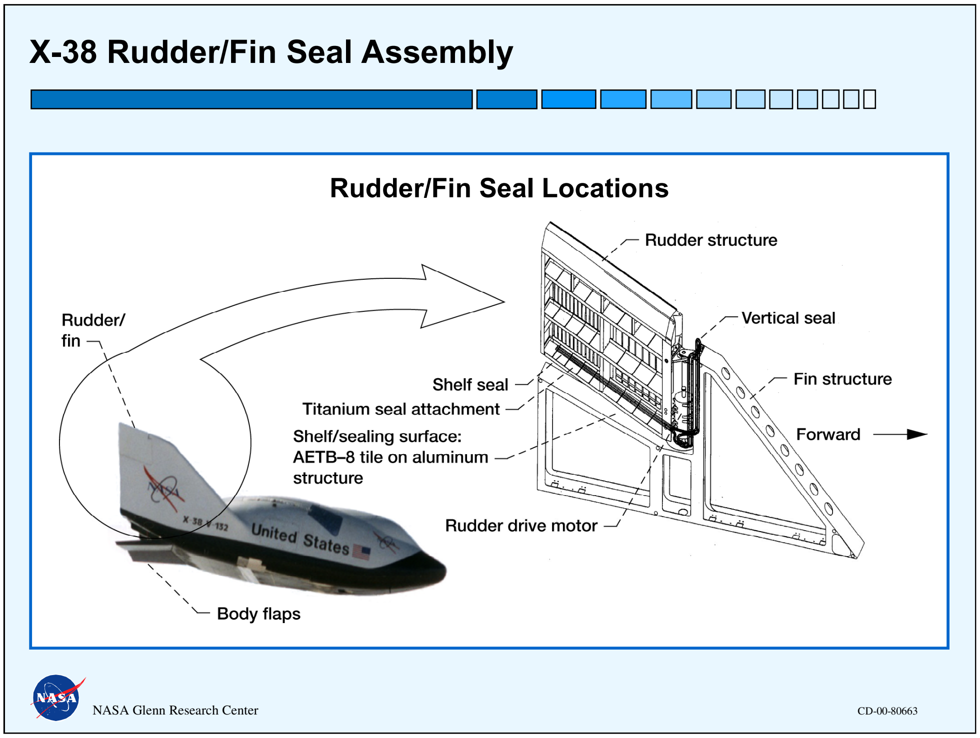
Background

- NASA developing X-38 vehicle to demonstrate technologies for crew return vehicle (CRV) for International Space Station. CRV will be "ambulance" for medical emergencies and evacuation vehicle.

- X-38 control surfaces (body flaps and rudders/fins) require high temperature seals to:
  - Limit hot gas ingestion
  - Limit transfer of heat to underlying low-temperature structures

- NASA Johnson Space Center and Glenn Research Center working together to develop and evaluate rudder/fin seals.
  - Measure seal flow rates, resiliency, and unit loads in as-received and temperature-exposed conditions
  - Compare measured results to property goals
  - Identify areas for future work

NASA is currently developing the X-38 vehicle that will be used to demonstrate the technologies required for a crew return vehicle (CRV) for the International Space Station. The CRV will serve both as an ambulance for medical emergencies and as an evacuation vehicle for the Space Station. Control surfaces on the X-38 (body flaps and rudders/fins) require high temperature seals to limit hot gas ingestion and transfer of heat to underlying low-temperature structures to prevent over-temperature of these structures and possible loss of the vehicle. NASA's Johnson Space Center (JSC) and Glenn Research Center (GRC) are working together to develop and evaluate seals for the rudder/fin control surfaces. The specific objectives of this study are to measure seal flow rates, resiliency, and unit loads in as-received and temperature-exposed conditions and compare the measured results to property goals where applicable. Areas for future work would then be identified.



This chart shows the X-38 vehicle including the body flap and rudder/fin locations where high temperature seals are required. The figure on the right shows an enlarged view of the rudder/fin seal location. The rudder/fin seals consist of a double seal attached to the surface of the rudder that seals the vertical hinge line and the fin shelf line. The vertical seal loop surrounds and protects the rudder drive motor and the attachments between the rudder and the fin. The shelf seal seals the gap between the bottom surface of the rudder and the shelf of the fin. The seals must allow the rudder to rotate during the entire mission and must accommodate a rudder/fin deflection range of ± 12 degrees. They also must not transmit excessive loads to the AETB-8 (Alumina Enhanced Thermal Barrier – 8 lb/ft^3 density) thermal tiles against which they seal so as not to damage the tiles.

Design Requirements for X-38 Rudder/Fin Seals

- **Temperature limits:** Thermal analysis predicted peak seal temperatures of 1900°F (with laminar boundary layer assumption) to 2100°F (with turbulent boundary layer assumption)
- **Pressure drop:** Maximum predicted pressure drop across seal is 56 lbf/ft^2 (0.4 psi)
- **Flow goal:** Preliminary flow goal of 4.2x10^{-5} lbm/sec per inch of seal at 56 lbf/ft^2
- **Resiliency:** No specific design requirement. Seals are to maintain contact with sealing surface during maximum heating cycle
- **Seal loads:** Unit load (load per unit inch) is to be less than 5 lbf/in. Contact pressure to be below 10 psi
- **Wear resistance:** Seals must allow rudder rotation without excessive loads on rudder drive motor
- **Life:** Single-use seal

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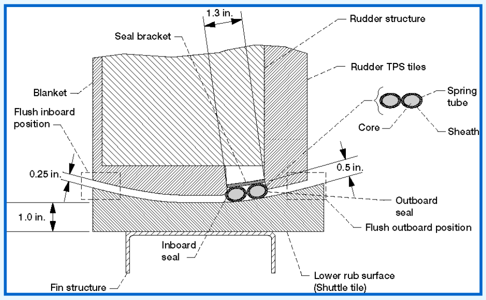
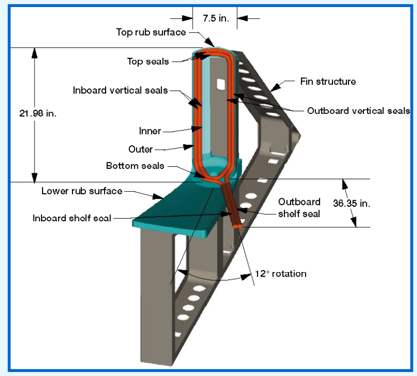
Design requirements were decided upon for the X-38 rudder/fin seals so that test results could be compared to an original set of property goals. An initial thermal analysis performed by JSC predicted peak seal temperatures of 1900°F (with a laminar boundary layer assumption) to 2100°F (with a turbulent boundary layer assumption). The maximum predicted pressure drop across the seal during vehicle re-entry was about 56 lbf/ft^2 (0.4 psi). An initial seal permeability value was used to calculate a preliminary flow goal along the length of the seal of 4.2x10^{-5} lbm/sec per inch of seal at 56 lbf/ft^2. In terms of seal resiliency, no specific design requirement was set. Designers at JSC only specified that the seals are to remain in contact with the opposing seal surfaces during the maximum heating cycle to prevent flow paths from developing around the seals. Because the seals will seal against Shuttle derived tiles that cannot withstand excessive loads, seal unit loads and contact pressures must be limited to prevent tile damage. Unit loads (load per linear inch of seal) were set to be less than 5 lbf/in, and contact pressures were to be below 10 psi. In terms of wear resistance and life, the seals are single use items that will be replaced after each mission. They also must not experience excessive wear as they are scrubbed over the surface of the fin shelf. Such wear could create loads on the rudder drive motor that would interfere with rudder rotation.

Baseline X-38 Rudder/Fin Seal Design

Cross Section of Rudder/Fin Seal Location



Computer Model of Rudder/Fin Seal



- **Main seal components**
  - **Core: 6, 9 pcf Saffil insulation**
  - **Spring tube: Inconel X-750**
  - **Sheath: Two layers of Nextel 312 fabric**
- **Seals are used on Space Shuttle: main landing gear doors, orbiter external tank umbilical door, payload bay door vents**
- **Nominal 20% compression and 0.25-in. gap**

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This chart shows details of the X-38 rudder/fin seal design. As seen in the figure on the left, the 0.62-in diameter seals are composed of an Inconel X-750 spring tube that is stuffed with Saffil insulation at either 6 or 9 lbf/ft^3 (pcf) density. Two layers of Nextel 312 fabric are braided over the spring tube. The 6 pcf design was chosen as the baseline seal design for this application, but the 9 pcf design was also tested for comparison purposes. These seals are currently used in several locations on the Space Shuttle orbiters including the main landing gear doors, the orbiter external tank umbilical door, and the payload bay door vents. The figure on the left shows a cross section of the rudder/fin shelf seal location as seen while standing aft looking forward. The double seals can be seen attached to a bracket in the rudder and compressed against the opposing surface of the fin shelf. The seals are compressed to a nominal 20% compression to seal a 0.25-in gap. The figure on the right shows the entire seal assembly including dimensions for the vertical loop and shelf seal portion. The shelf seals are shown rotated 12 degrees off of the shelf. In this position, a portion of the seals are no longer in contact with the shelf and are exposed to the hot gases that are passing over the vehicle. As the seals are moved back on to the shelf surface, they will be compressed again and must be able to endure the shear forces that they will be subjected to without causing excessive loads on the rudder drive motor.

Test Matrix

Compression Testing

Compression level	20%		25%		30%	
	Primary	Repeat	Primary	Repeat	Primary	Repeat
6 pcf as-received	✓	✓	✓	✓	✓	✓
6 pcf after time at 1900 deg F	✓	✓	✓	✓	✓	✓
9 pcf as-received	✓	✓				

Flow Testing

Gap size	0.25 in				0.13 in			
Compression level	20%		25%		20%		25%	
	Primary	Repeat	Primary	Repeat	Primary	Repeat	Primary	Repeat
Single seal								
6 pcf as-received	✓	✓	✓		✓		✓	
6 pcf after time at 1900 deg F	✓	✓	✓		✓		✓	
9 pcf as-received	✓	✓						
Double seal								
6 pcf as-received	✓							

✓ Checked blocks indicate tests performed

- **Each test used a separate seal specimen**

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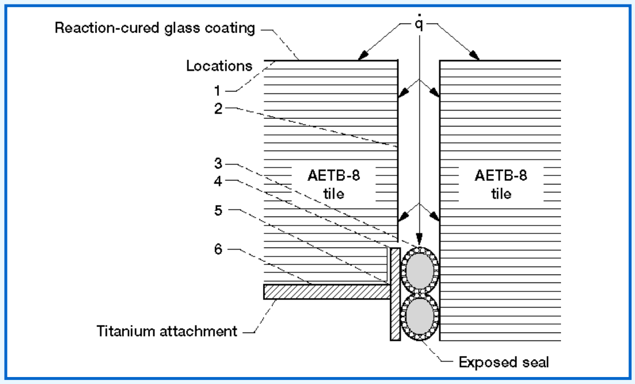
This chart shows the matrix of tests that were completed at GRC on the rudder/fin seals. A series of room temperature compression and flow tests were performed on two different seal designs under a variety of test conditions. The checked blocks indicate tests that were performed, and each test used a separate seal specimen. Compression tests were performed to determine the preload and resiliency behavior of the seals. Primary and repeat tests were done at three different compression levels (20, 25, and 30%) on the 6 pcf design in both the as-received state and after temperature exposure at 1900°F. Primary and repeat tests were done at 20% compression on the 9 pcf design in the as-received state for comparison purposes. Flow tests were performed at two different gap sizes (0.25 in. and 0.13 in.) and two different compression levels (20 and 25%). Single seals were flow tested for the 6 pcf design before and after temperature exposure and for the 9 pcf design in the as-received state. A double seal flow test was performed on the 6 pcf as-received seal at 20% compression with a 0.25-in gap.

Thermal Analysis - Rudder/Fin Seal Thermal Model



- Thermal analysis used quasi-2-D representation of tiles (AETB-8 with RCG/TUFI coating), dual seals, and titanium attachment
- Model accounted for conduction, convection, and radiation but no flow through permeable seal. Heat fluxes to seal and gap walls estimated using Nestler gap heating correlations (Nestler, AIAA72-717) using reference heating on windward surface of rudder/fin area as input

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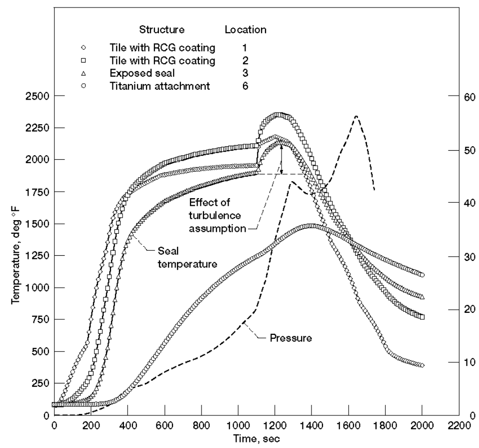
This chart shows the thermal model that JSC used to predict temperatures for the rudder/fin seals and surrounding hardware during re-entry of the X-38 vehicle. The model is a quasi-two-dimensional representation of the tiles (AETB-8 with RCG/TUFI coating), the dual seals, and the titanium seal attachment. It accounted for conduction, convection, and radiation down into the seal gap, but it did not account for flow through the permeable seals. We believe that including flow through the seals in the model could effect temperature predictions and result in higher predicted maximum seal temperatures. Heat fluxes to the seal and to the gap walls were estimated using the gap heating relationship presented by Nestler (Nestler, AIAA 72-717). Reference heating conditions on the windward surface of the rudder/fin area during re-entry of the X-38 vehicle were used as the input for the model.

Thermal Analysis- Rudder/Fin Seal Temperature Predictions

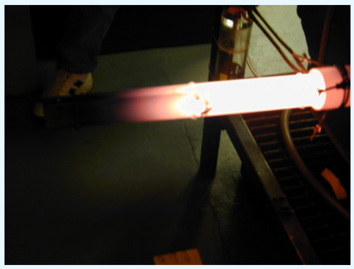


- **Predicted peak seal temperatures of 1900°F (with laminar boundary layer assumption) to 2100°F (with turbulent boundary layer assumption)**
- **Predicted peak pressure of 56 lbf/ft ^{2}**

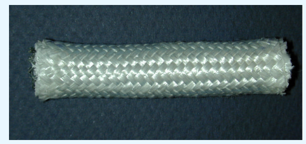
The results of the rudder/fin seal thermal analysis performed by JSC are shown in this chart. The plot shows temperature predictions for several locations in the model versus time during re-entry. Also shown is the predicted pressure differential across the seal during re-entry. The third line down shows the predicted seal temperatures. The thermal analysis predicted a maximum seal temperature of 1900°F (with a laminar boundary layer assumption) to 2100°F (with a turbulent boundary layer assumption). The dashed line is the predicted pressure differential across the seal showing a peak pressure of 56 lbf/ft^2 (psf). The plot shows that the peak seal temperature and pressure are not coincident, but the testing that we performed was done as if they did occur at the same time to simulate worst case conditions.

Temperature Exposure

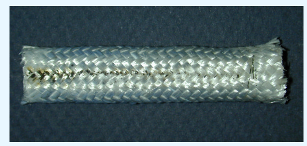
Temperature Exposure of X-38 Seal



As-received



After Temperature Exposure

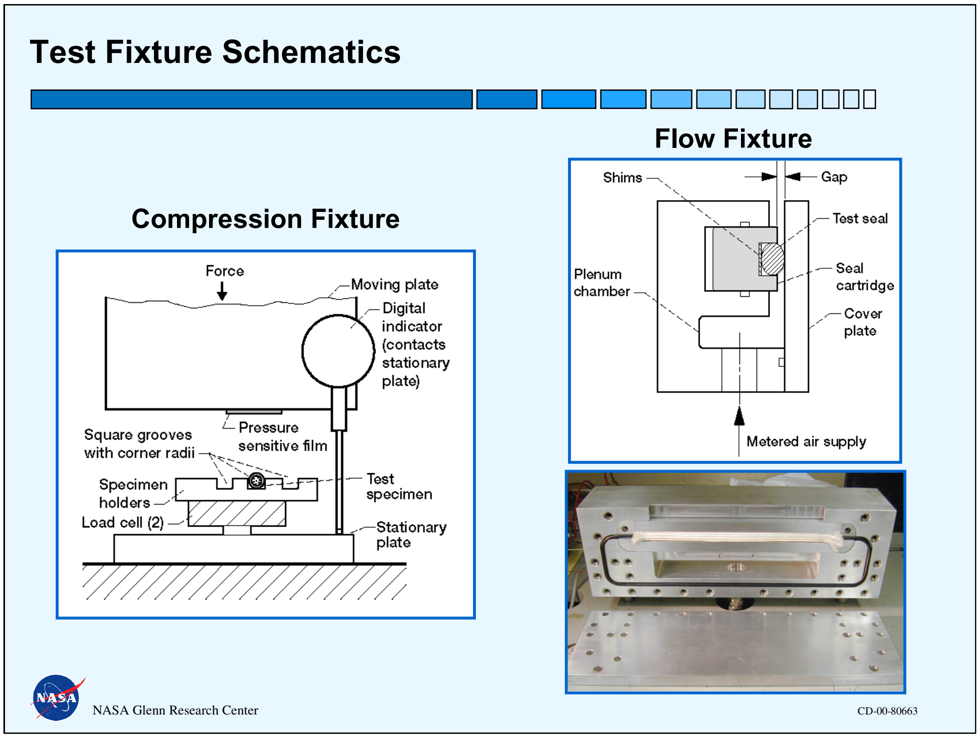


Test Conditions:
- Exposed 6 pcf seals to 1900°F in compressed state for 7 minutes

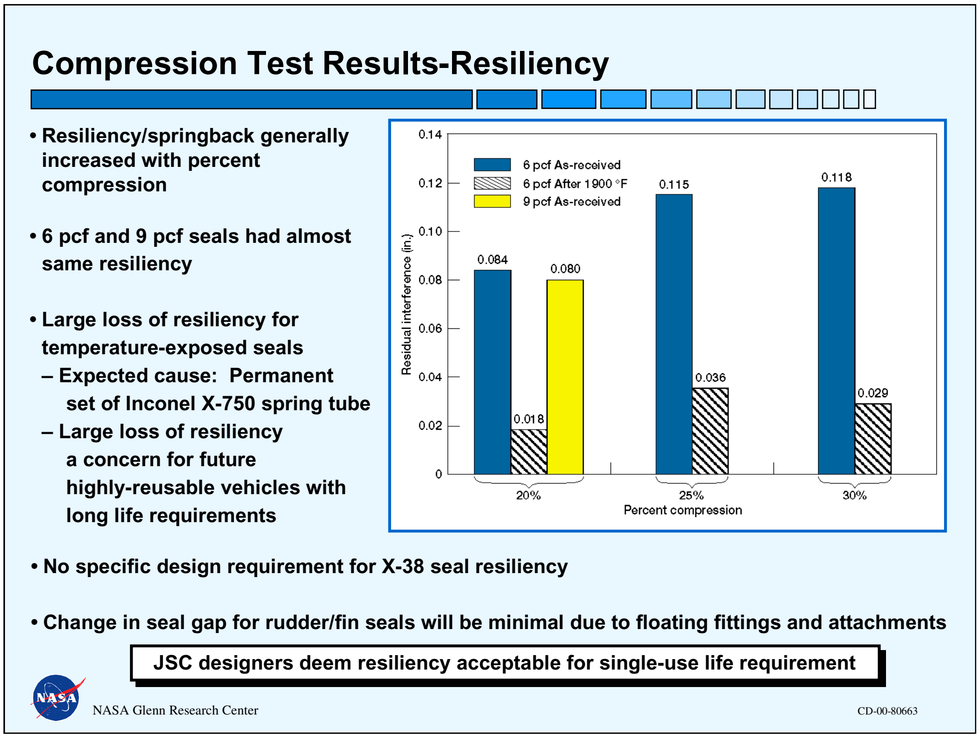
Observations:
- Seals took on elliptical cross section and became stiffer and less flexible
- Loss of resiliency believed to be due to permanent set of Inconel X-750 spring tube (yield strength at 1900°F < 5% of room temperature strength)
- No noticeable changes to Nextel 312 fabric or Saffil batting

Seals lost resiliency and took on large permanent set

Temperature exposure tests were done on the 6 pcf seal design to simulate exposure to the extreme temperatures predicted by the thermal analysis and to determine the effects that this exposure has on the seals. The tests were conducted by placing specimens into a tube furnace in a compressed state and heating them at 1900°F for seven minutes. The figure on the left shows a hot seal specimen being removed from the furnace in its test fixture. After temperature exposure, the seals took on an elliptical cross section (lower right figure) compared to the circular cross section of an as-received seal (upper right). The seals took on a large permanent set and became stiffer and less flexible than they were before the temperature exposure. We believe that this loss of resiliency is due to permanent set of the Inconel X-750 spring tube whose yield strength at 1900°F is less than 5% of its room temperature strength. There were no noticeable changes after temperature exposure to the Nextel 312 fabric outer sheath or the Saffil batting in the core of the seals. This loss of seal resiliency would be a problem for a reusable vehicle in which the seals must remain resilient after multiple heating cycles. The X-38 only requires single-use seals, though, so this seal design should be resilient enough for one vehicle re-entry.



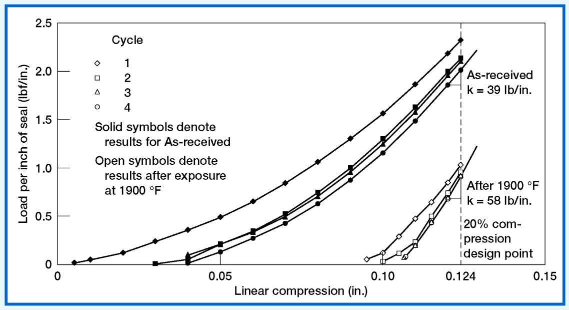
This chart shows schematics for our compression (left) and flow (right) fixtures. In the compression fixture, a test specimen is loaded into a stationary grooved specimen holder, and an opposing plate is compressed against the specimen. Load cells behind the specimen holder record the amount of load on the seal, and the displacement of the movable opposing plate against the specimen is shown on a digital indicator. Multiple load cycles are applied to a specimen to remove the effects of hysteresis that accumulate with load cycling. Typically four load cycles are applied to each specimen. A pressure sensitive film mounted on the opposing plate is used to determine the contact width of the specimen as it is loaded. The footprint length and width at the end of the fourth load cycle are used to calculate seal preload or contact pressure. Flow tests are performed using the ambient linear flow fixture shown in the two figures on the right. The fixture is designed so that single or double seals of different diameters can be tested in removable cartridges that are inserted into the main body of the test fixture. Shims are inserted into the groove behind the seal to vary the amount of linear compression on the seal. Spacer blocks of different thicknesses are placed at each end of the cartridge to vary the gap that the seal is sealing between the cartridge and the cover plate. During a test, flow enters through the bottom of the fixture, passes through a plenum chamber, and flows through the gap that the seal is sealing. A flow meter upstream of the fixture measures the flow rate through the seal while the pressure differential across the seal and the temperature upstream of the seal are measured inside the fixture.



This chart shows some of the results of our compression tests. The plot shows the amount of resiliency, or springback, for different test conditions and compression levels. The different color bars are for the 6 pcf design in the as-received state (blue bar), the 6 pcf design after temperature exposure (striped bar), and the 9 pcf design in the as-received state (yellow bar). In the plot, residual interference refers to the amount that a seal springs back after it has been compressed for four load cycles. For example, if the 0.62-in diameter 6 pcf as-received seal is compressed 20% (0.124 in), it springs back for a residual interference of 0.084 in. Thus, the seal has taken a permanent set of 0.040 in. Looking at the results overall, seal resiliency generally increased as the percent compression on the seals was increased from 20% to 25% to 30%. The 6 pcf and 9 pcf as-received seals had almost the seal resiliency at 20% compression. Thus, using the denser core in the 9 pcf design did not add any additional resiliency to this seal design as compared to the 6 pcf design with a less dense core. The temperature-exposed 6 pcf seals took on a large permanent set and lost a large amount of resiliency. Again, this is believed to be due to permanent set of the Inconel X-750 spring tube. The loss of resiliency for this seal design is a concern if this seal is to be used in future highly reusable vehicles with long life and high resiliency requirements. For the X-38 vehicle, there was no specific design requirement, so these seal designs should be resilient enough for a single use. The rudder/fin assembly of the X-38 was designed with floating fittings and attachments, so the change in gap size that the seal is sealing will probably be minimal.

Compression Test Results-Loads

Load versus Compression Data for 6 pcf Seal



- **Unit loads (load per inch of seal) and contact pressures were higher for as-received seals**
  - **Due to loss of resiliency and smaller contact width for temperature-exposed seals**
- **Temperature-exposed seals were 1.5X stiffer than as-received seals at 20% compression**
  - **Oxidation and deformation of Inconel X-750 spring tube increased roughness of wires and made seals stiffer**
- **Unit loads (2 lb/in.) and contact pressures (4.4 psi) below 5 lb/in. and 10 psi limits (Limit loads on Shuttle thermal tiles, AETB-8 with RCG/TUFI coating)**

Seal unit loads met goal in both as-received and temperature-exposed conditions

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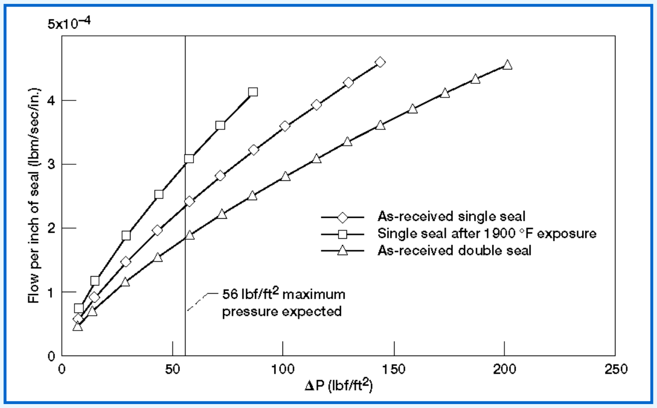
This chart shows the results of the loads measured in our compression tests. The plot shows the load versus displacement curves for four load cycles at 20% compression on the as-received and temperature-exposed 6 pcf seals. The plot shows that the seals do take on a permanent set as they are exposed to more load cycles, but the curves for each successive cycle tend to collapse on to each other by the fourth load cycle. It can be seen clearly how much permanent set the temperature-exposed seal has taken on. Using the same starting point for a temperature-exposed seal as for the as-received seal, the opposing plate is moved roughly 0.1 in. before it even contacts the seal for the first few load cycles. This contributed to a difference in loads measured on each seal. The unit loads (load per linear inch of seal) and contact pressures were higher for the as-received seals than for the temperature-exposed seals even though the temperature-exposed seals felt stiffer and less flexible. This was due to the loss of resiliency and smaller contact widths of the seals after temperature exposure. However, the temperature-exposed seals were stiffer than the as-received seals. The slope through the last two data points on the fourth load cycle was 1.5 times larger for the temperature-exposed seals than for the as-received seals at 20% compression. This is believed to be due to oxidation and deformation of the Inconel X-750 spring tube causing the wires to become rougher and less able to slide past each other. All of the seal designs that were tested had unit loads and contact pressures below the 5 lb/in and 10 psi limits that were set to limit loads on the Shuttle thermal tiles that the seals will be in contact with in the rudder/fin application. Thus, these seal designs met the property goals for unit loads and contact pressures.

Flow Test Results-Effect of Temperature Exposure

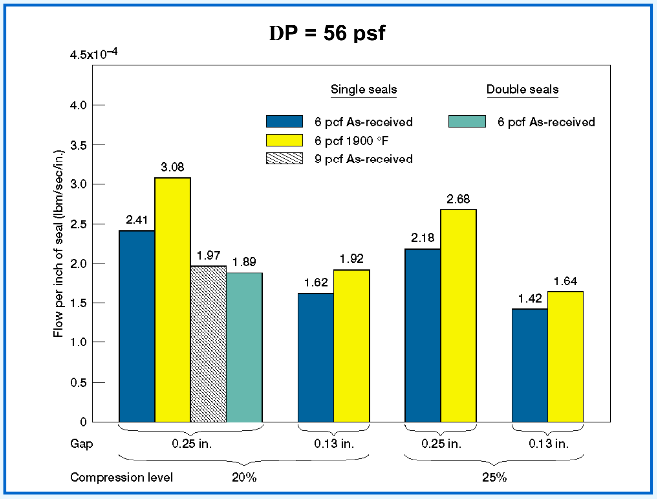
Flow versus Pressure Data for 6 pcf Seal



- **Temperature-exposed seals exhibited 28% higher flow rates than as-received seals at 56 lbf/ft ^{2}**
- **Expected cause: Loss of load per unit inch and smaller contact footprint width lead to higher flow rates through seal and sealing contact for temperature-exposed seals**

This chart shows flow data for the 6 pcf seal design. The flow rate in lbm/sec/in along the length of the seal is plotted versus the pressure differential across the seal for single as-received and temperature-exposed seals and for double as-received seals. This plot shows that temperature exposure of the 6 pcf seals caused an increase in flow rate through the seals of 28% as compared to the as-received seals at a differential pressure of 56 lbf/ft^2. This is believed to be due to the loss of load per unit inch and smaller contact footprint width caused by temperature exposure of these seals. A narrower contact footprint reduces the contact area between the seal and the adjacent structure and leads to higher flow rates through the seals. This plot also shows that adding another seal into the flow path reduced the amount of flow through the seals as compared to only a single seal. This will be discussed further on the next chart.

Flow Test Results



- Flow rates decreased with increase in compression levels and decrease in gap size
- Lower flow rates for as-received 9 pcf seal than for as-received 6 pcf seal
  - Denser core in 9 pcf seal blocked more flow

- Flow rates through double 6 pcf as-received seals were 22% lower than for single seals but were 4.5X higher than preliminary flow goal

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Additional flow test data is presented in this chart. Flow rates are presented for several different seal types and conditions at a pressure differential of 56 lbf/ft^2. Single seal flow rates are given for 6 pcf as-received (blue bars) and temperature-exposed seals (yellow bars) and for 9 pcf as-received seals (striped bars). Flow data is also given for double 6 pcf as-received seals (green bars). Data is shown for two different compression levels (20 and 25%) and two gap sizes (0.25 in. and 0.13 in.). Flow through the seals decreased as the amount of compression on the seals was increased. This was expected because increasing the amount of compression on the seals closed the gaps and flow paths in their porous structure and allowed less flow to pass through them. Similarly, reducing the gap size from 0.25 in. to 0.13 in. also lowered the amount of flow through the seals. This was also expected because a reduction in gap size decreased the flow area through the seals and further limited the seal area that was in the flow path. Lower flow rates were measured for the as-received 9 pcf seal than for the as-received 6 pcf seal. The denser core of the 9 pcf design blocked more flow through the seal. Flow rates through double 6 pcf as-received seals were 22% lower than for a single seal at the same compression level. Adding a second seal did not cut the amount of flow through the seals in half, but this type of behavior has been observed previously in multiple-seal flow tests (Steinetz, et al., Journal of Propulsion and Power, Vol. 14, No. 6, 1998, pp. 934-940). Flow rates through the double seals were 4.5 times higher than the preliminary flow goal.

Summary and Conclusions

- **Exposure of seals in compressed state at 1900°F resulted in loss of resiliency due to permanent set of Inconel X-750 spring tube. Not a problem for single-use seals.**
- **Unit loads and contact pressures were below 5 lb/in. and 10 psi limits. Low loads required to limit damage to Shuttle thermal tiles.**
- **Flow rates for double as-received 6 pcf seal about 4.5 times higher than preliminary flow goal**
  - **— Effect of measured flow through porous seal on maximum seal temperature requires further examination**
- **Seal designs expected to endure peak seal temperatures for single-use life**

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In summary, temperature exposure of these seals in a compressed state at 1900°F resulted in a large loss of resiliency due to permanent set of the Inconel X-750 spring tube. This is not anticipated to be a problem for the single-use X-38 rudder/fin application where the seals can be replaced after each mission. However, these seal designs would not work well in applications where reusable, resilient seals are required that can endure high temperatures without taking on a large permanent set. The unit loads and contact pressures measured for these seals were below the 5 lb/in and 10 psi limits that were set to limit the amount of damage that these seals would cause in adjoining Shuttle thermal tiles on the rudder/fin. Flow rates for double 6 pcf as-received seals were about 4.5 times higher than the preliminary flow goal. We believe that these measured flow rates should be incorporated into the thermal model to see how the effects of seal porosity influence the maximum seal temperature. Overall, these seal designs are expected to endure the peak seal temperatures and anticipated environment for a single-use life in the X-38 rudder/fin application.

Future Work/Recommendations

- Perform more detailed thermal analyses including flow through permeable seal to assess effects on maximum predicted seal temperatures

- Perform additional flow tests representative of application:
  - — After scrubbing
  - — Under low seal preload conditions (0%, 10% compression)
  - — With fabric as opposing surface

- Perform arc jet tests (part of Spaceliner-100 program) and scrubbing tests (at JSC) to assess seal performance under simulated environments

NASA JSC and NASA Glenn are currently evaluating best approaches to address these issues

NASA JSC and GRC are currently discussing what additional work will be done to evaluate these seals. GRC has recommended that more detailed thermal analyses be performed to include flow through the permeable seals and to assess how this affects maximum predicted seal temperatures. Additional flow tests will probably be performed to examine seal flow rates after scrubbing, under low preload conditions (0%, 10% compression), and possibly with fabric as the surface in contact with the seals. A series of arc jet tests will be performed as part of the Spaceliner-100 program in which these same seal designs will be used as the baseline designs. JSC is also planning to do more scrubbing tests on these seals. These tests will be done to assess seal performance under simulated environments.